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Magneto-tunnelling spectroscopy of localised and extended states in a quantum well containing quantum dots

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Abstract. We investigate resonant tunnelling in GaAs/(AlGa)As double-barrier resonant-tunnelling diodes (RTDs) in which a single layer of InAs self-assembled quantum dots (SAQDs) is embedded in the centre of the GaAs quantum well. The dots provide a well-defined and controllable source of disorder in the well and we use resonant tunnelling for studying the effect of disorder on the electronic properties of the well.

A thin pseudomorphic InAs layer (wetting layer-WL) incorporated in the central plane of an (AlGa)As/GaAs/(AlGa)As quantum well (QW) leads to a significant lowering of the energy of the quasi-two dimensional (2D) ground state subband of the QW [1]. Above a critical wetting layer thickness, self-assembled InAs quantum dots (SAQDs) are formed. This modifies further the electronic states of the system: firstly, the dots give rise to discrete zero-dimensional bound states and, secondly, they create a considerable amount of disorder, which influences the properties of the continuum of wetting layer subband states. The disorder is a consequence of the fluctuating random potential arising from local strains and charging of the quantum dots. Within a single-electron picture, it could change the localisation length of the 2D states.

In this work, we investigate resonant tunnelling in MBE-grown GaAs/(AlGa)As double-barrier resonant-tunnelling diodes (RTDs) in which a single layer of InAs SAQDs is embedded in the centre of the GaAs QW. These RTDs form a flexible “quantum laboratory” for investigating a variety of phenomena, including the dynamics of carrier tunnelling, capture and recombination [1] and the spatial distribution of the probability density of the electron wave function in the dots [2]. Here we use resonant tunnelling spectroscopy to demonstrate that the random potential in the well due the presence of dots strongly influences the electronic properties of the disordered ground state two-dimensional subband in the QW.

Three different structures were investigated: Sample *qd* comprised (in the order of growth) a lightly Si-doped, 300-nm-thick GaAs layer ($N_d = 3 \cdot 10^{18} \text{ cm}^{-3}$); a 50.4-nm-thick GaAs layer ($N_d = 2 \cdot 10^{18} \text{ cm}^{-3}$); a 50.4-nm-thick undoped GaAs spacer layer; a 8.3-nm-thick $\text{Al}_{0.4}\text{Ga}_{0.6}\text{As}$ barrier layer; a 5.6 nm undoped GaAs layer; a 1.8 monolayer

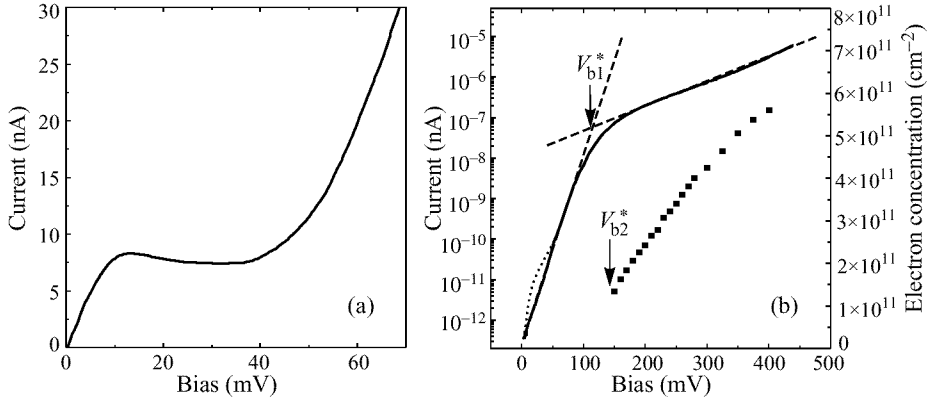


Fig. 1. (a) Low bias I–V curve of the sample with only wetting layer. (b) Logarithmic plot of the current versus voltage dependence of the tunnelling current for the sample with embedded in the well quantum dots (solid line, left scale). Dotted line shows extra current which appears only at positive bias. V_{b1}^* and V_{b2}^* are described in the text. Squares show concentration of electrons in the accumulation layer versus bias (right scale).

(ML) InAs with growth rate 0.13 ML/s to form InAs QD; a 5.6-nm-thick undoped GaAs layer; a 8.3-nm-thick $\text{Al}_{0.4}\text{Ga}_{0.6}\text{As}$ barrier; a 50.4 nm undoped GaAs; a 50.4-nm-thick GaAs layer ($N_d = 2 \cdot 10^{18} \text{ cm}^{-3}$); and a 300-nm-thick GaAs layer ($N_d = 3 \cdot 10^{18} \text{ cm}^{-3}$) cap-layer. Two control samples were also grown. One had only an InAs wetting layer (sample *wl*) in place of the QDs and the other had no InAs layer at all.

The presence of the narrow InAs WL modifies the electronic structure of the QW lowering ground state down below the GaAs conduction band edge whereas the excited QW subbands are relatively unaffected. Simple self-consistent calculations of Schrödinger and Poisson equations show that ground state in the sample with wetting layer only is located about 50 mV below the GaAs conduction band edge and filled with electrons from contact layers. The ground state is in resonance with 3D electrons in contacts at zero bias. This is illustrated in Figure 1(a). The resonance feature is observed at $V_b = 0$ and NDC corresponding to the exit from resonance is around 30 mV. The control sample without the InAs wetting layer shows resonant tunnelling features in $I(V)$ due to the tunnelling through the unperturbed ground state in the well at higher bias voltage, $V_b = 0.1 \text{ V}$.

For the sample in which the dots are formed (sample *qd*), a wetting layer is still present and the overall effect on the energy spectrum is to add zero-dimensional bound states below the ground state level. The negative charging of the dots by electrons from the contacts could only shift up the ground state relatively to the equilibrium Fermi level in the RTD. This means that the resonance condition between the 3D electrons in the doped contact layers and ground state subband remains at zero bias, or shifts to higher bias, depending on the QD density in the layer. Therefore, for the QD sample, we would also expect to see a resonant tunnelling feature in $I(V)$ associated with the ground state subband.

In contrast to this expectation, the I–V curve of the sample *qd* shows only exponential increase of the current with bias voltage (Fig. 1(b)). Nevertheless there are two distinct features in the curve. First, the exponential current onset changes exponent at around $V_{b1}^* \approx 110 \text{ mV}$. Secondly, there is a shoulder in the current below 50 mV appeared only at positive bias (shown by dotted line). We associate the shoulder with tunnelling through excited states in the quantum dots and will discuss it in detail elsewhere. Here we focus on the two exponents in the I–V curves.

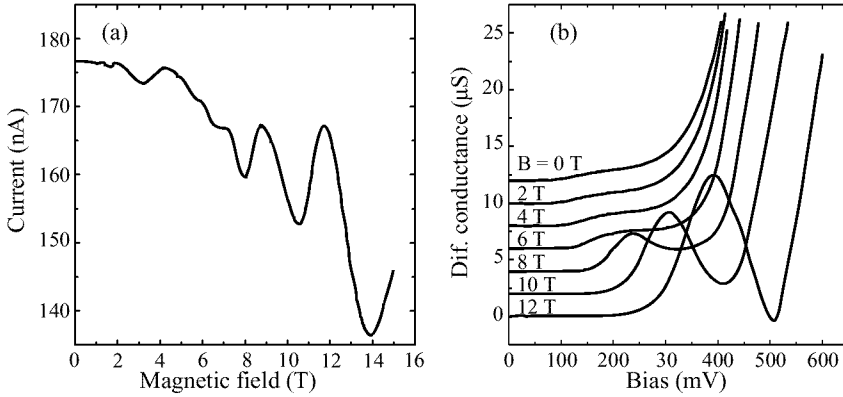


Fig. 2. (a) Variation of the tunnelling current with normal magnetic field at 300 mV bias voltage. (b) Differential conductance of the sample with quantum dots versus bias voltage in different in-plane magnetic fields.

In order to understand the absence of any resonant current features related to the ground state in the sample *qd*, we need to take into account that the layer of charged dots is a source of strong potential fluctuations. This leads to a non-uniform broadening of the ground state level in the well and strong localisation of the corresponding two-dimensional electron states. Then, if the localisation length of the final states is comparable with the Fermi wavelength of the electron tunnelling from the emitter, momentum conservation is destroyed and only energy conservation is important for the tunnelling process. In the sequential resonant tunnelling model, it is the conservation of the in-plane momentum that leads to the current peaks and the NDC regions in the $I(V)$ curves [3]. Thus we argue that the exponential increase of the current at low bias simply reflects tunnelling through strongly localised two-dimensional states in the well with no momentum conservation.

In tunnelling experiments the exponential I - V dependences arise since the tunnelling current exponentially depends on the barrier height and/or effective barrier thickness. At low bias electrons in the 3D contacts tunnel to the states in the well across the complex barrier involving the spacer layer and the main AlGaAs barrier. At higher bias voltage above some critical value V_{b1*} when the 2D accumulation layer is formed near the main barrier only the last one determines tunnel exponent. It is easy to show that for these two cases we should have different exponents.

Magnetotunnelling data obtained in the field normal to the layers confirm the formation of the accumulation layer above V_{b1*} . Figure 2(a) shows variation of tunnel current versus magnetic field at $V_b = 300$ mV. There are two distinct series of oscillations each periodic in $1/B$. It follows from analysis of the data that low magnetic field oscillations (below 4 T) are due to the electron concentration variation in the accumulation layer with magnetic field. Oscillations in a high magnetic field reflect the tunnelling through empty Landau states in the quantum well. In the field higher than 4 T only ground Landau level in the accumulation layer emitter is occupied and all tunnelling electrons have approximately the same energy. Consequently magnetotunnelling spectra measured at constant bias reflects the variation of the density of state at some fixed energy in the well with magnetic field. Electron concentration in the accumulation layer versus voltage bias determined from the low magnetic field oscillations is shown in Fig. 1(b) by squares. The electron concentration comes to zero just at V_{b1*} .

It should be noted that both sets of magneto-oscillations appear simultaneously at bias voltage $V_{b2^*} \approx 140$ mV. Below this bias no any oscillations have been resolved in the sample containing QD. In the wetting layer sample tunnelling through Landau states in the well was observable at all voltages. If appearance of low field oscillations is as usual related with formation of the accumulation layer continues along barrier, the appearance of high field oscillations one should relate with formation of Landau states in the presence of random potential only above some energy E^* in the well. This apparent (seeming) threshold between localised and delocalised states can simply be explained in terms of random potential screening by electrons in the accumulation layer after its formation. Estimations based on the theory developed by Davies [4] show that for our structure dispersion of the random potential in the well is reduced about ten times after the accumulation layer formation.

This model explains also surprising from the first glance appearance of the negative differential conductance in the I–V curves in magnetic field perpendicular to the tunnel current (Fig. 2(b)). In common RTDs the resonant peak is shifted to higher biases with in-plane magnetic field [5]. It happens because Lorentz force change the in plane momentum of tunnelling electron shifting bias voltage where both momentum and energy conservation conditions are satisfied to higher value. In in-plane magnetic field in resonance electrons tunnel to the states with higher energy in the well relative to the case $B=0$. Since, if there is threshold energy E^* in our structure, one could expect appearance of negative differential conductance region in I–V curves in in-plane magnetic field when electrons start to tunnel into the states above E^* with momentum and energy conservation.

In conclusion, we have studied details of resonant tunnelling through AlGaAs/GaAs/AlGaAs double barrier heterostructures (DBHS) with InAs self-assembled quantum dots embedded in the well region. The I–V curves show only exponential increase of the current with bias voltage without any features reminding resonant tunnelling through the ground state in the well, e.g. current peaks or negative differential conductance regions. This is related with tunnelling through the tails of strongly localised two dimensional states in the well with only energy conservation. The strong localisation of the states is due to the random potential originated from local strains in the InAs layer and charging of the quantum dots. At high enough bias voltage the 2D accumulation layer formed near the main barrier reduces dispersion of the random potential in the well by screening. As the result the formation of Landau states above some energy E^* in the well have been observed. The tunnelling into the states above E^* with momentum conservation have been also found in the in-plane magnetic field.

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